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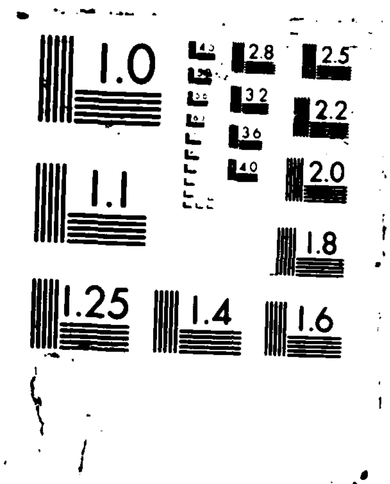
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Final Technical Report

"Repetitive Opening Switches Using
Optically Activated Semiconductors"

Grant No. AFOSR-84-0359

Submitted by:

Dr. Chi H. Lee

Dr. M. J. Rhee

Electrical Engineering Department
University of Maryland

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This is the final technical report for a research program to study repetitive opening switches using optically activated semiconductors. This program was funded by the Air Force Office of Scientific Research for the period 1 September 1984 to 31 August 1987 under Grant No. AFOSR-84-0359. The goal of this research was to study opening switch characteristics of various semiconductors in conjunction with inductive energy storage systems.

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Final Technical Report

REPETITIVE OPENING SWITCHES USING OPTICALLY ACTIVATED SEMICONDUCTORS

Grant No. AFOSR-84-0359

For the Period September 1, 1984 to August 31, 1987

Submitted to

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October 1987

Submitted by

Department of Electrical Engineering
University of Maryland
College Park, Maryland 20742

TABLE OF CONTENTS

ABSTRACT

This is the final technical report for a research program to study repetitive opening switches using optically activated semiconductors. This program was funded by the Air Force Office of Scientific Research for the period September 1, 1984 to August 31, 1987 under Grant No. AFOSR-84-0359. The goal of this research was to study opening switch characteristics of various semiconductors in conjunction with inductive energy storage systems.

I. INTRODUCTION

Studies of optically activated semiconductor opening switches have been pursued at the University of Maryland under Air Force Office of Scientific Research sponsorship since 1984. During the past grant period, we have made significant progress in our studies. Our studies in this new area of opening switch, have been largely of exploratory nature. Initial work has centered around the understanding of basic opening switch phenomena in the semiconductors, and confirmed that semiconductors as well as other materials such as highly oriented pyrolytic graphite can be used for a light controlled opening switch with excellent switching characteristics. We have successfully demonstrated for the first time the generation of pulse by using a semiconductor opening switch. Since the optically controlled semiconductor switches have by far the fastest opening time, it was possible to produce a square-wave pulse by using a semiconductor switch and a current charged transmission line system which requires an extremely fast opening switch. After the basic studies with miniature scaled planar switches, we have also studied the high voltage scaling of the semiconductor switches. We have found bulk type switch of millimeter size with a pulsed infra-red laser can be easily operated at several kilovolt system, indicating clearly that such type of semiconductor switch are prime candidate for the high power opening switch application.

In this final technical report, we summarize the achievements we have made during the past three year grant period.

II. PROGRESS REPORT

1. Demonstration of Repetitive Semiconductor Opening Switch

The first demonstration of repetitive semiconductor opening switch was reported in a paper entitled "Optically Activated Semiconductors as Repetitive Opening Switches", published in the Applied Physics Letters, 47, 1293 (1985), and enclosed in Appendix B. Semiconductors used for the opening switch include GaAs and Fe:InGaAs in a planar geometry, and 1 ns rise time with 10 Hz repetition rate and jitter free operation of the switch was demonstrated. These switches are potentially capable of operating at very high repetition rates. Because of the small gap width used (4 and 200 μm) and the limited laser power available, the experiment was performed at low voltage (20 V). The main difficulty we found was to lower the on-state switch resistance. With the best case with available low power of CW Argon laser, the on-state resistance obtained was 150 Ω, which limits the efficiency of the system.

2. Generation of Square Pulses

Since the semiconductor switch has demonstrated a very fast opening time, it was possible to couple the switch with a current charged transmission line, and for the first time the generation of ns square pulses in an inductive energy storage system was demonstrated. This study was summarized in a paper "A New Method to Generate Square Pulses: Optoelectronic Switching in Current Charged Transmission Lines", published in the IEEE Transactions on Plasma Science, PS-15, 70, (1978), and enclosed in Appendix B.

These results indicated that jitter-free square pulses of any desired pulse duration ranging from ns to μs can be generated. This technique may be the

ultimate goal of inductive energy storage systems in generating a high power pulse by high pulse compression. All of the advantages of the semiconductor switch including high repetition rate, long conduction time, jitter free operation, and fast rise time are well utilized in this application. The energy transfer efficiency from the transmission line to the load is nearly 100%.

3. Study of Switch Materials

Characteristics of switches made of different materials such as GaAs, Cr:GaAs, and Fe:InGaAs, with the gap size ranging from 4 to 200 μm and different gap geometries were studied. The results are summarized in a paper "Repetitive Semiconductor Opening Switch and Application to Short Pulse Generation", submitted to the Laser and Particle Beams for publication, and enclosed in Appendix B. The opening time of 1 ns obtained with switches made of Cr:GaAs and Fe:InGaAs is rather due to the rise time of Pockel's cell electronics. The carier recombination time of the materials were measured to be in the picosecond range which would be the ultimate limit of the switch opening time. The same difficulty of lowering the on-state resistance was found in all of the switches indicating that use of infra-red laser light, which provides a deep penetration depth in the material, thus larger conduction cross sectional area, is imperative for high power applications.

4. Studies of Bulk Geometry H.V. Switches

During the last year, we have made an attempt to use a pulsed infra-red laser for larger switches to operate at high voltage. The switch geometry was changed to a bulk type from the planar type previously used. Two electrodes were attached to opposite sides of a semiconductor cube of typically 2 to 6 mm in length. These millimeter-size gaps can easily hold several kilovolts. We

experimented with different fabrication techniques to optimize the breakdown through the air between the electrodes. The infra-red light generates carriers across the entire bulk of the switch via two-photon absorption, increasing the cross-sectional area of the carrier path, thus increasing the total current being sustained by the switch. The infra-red laser used was a Q-switched Nd:YAG laser which provide light pulses with wavelength 1.06 μm, pulse duration of 30 ns, and energy of 10 mJ. Some of the switches tested could sustain a voltage over 10 kV without breakdown. Use of this infra-red laser pulse reduced the on-state resistance as low as 5 Ω, which is mostly due to contact resistance. No attempt has been made yet to shape the laser pulse with a Pockel's cell to reduce the switch opening time, as it was done in the experiments, with the Argon laser. The best opening time obtained is thus equal to the laser pulse fall time which is 10 - 15 ns. The switch conduction time is limited to 30 ns by the available laser pulse duration. Thus for a system requiring a longer current chargeing duration it is necessary to develop a new laser with longer pulse duration. The results of bulk type switches are extremely encouraging and show a promise that the semiconductor switch can be used in a high power inductive energy storage system as an opening switch.

5. Graphite Opening Switch

We have also investigated opening switch characteristics of grphite which is a completely new material. The graphite used was Highly Oriented Pyrolytic Graphite (HOPG), which is a semimetal with a very high conductivity in its normal dark state. We demonstrated that, when illuminated with a high power picosecond laser light, resistivity of HOPG changes very rapidly to a high resistive state. The recovery time of this material was found to be in microsecond range

indicating that HOPG can be also a good candidate for a repetitive opening switch. The results of this experiment are summarized in a paper "Graphite Picosecond Optoelectronic Opening Switch", published in the Applied Physics Letters, 50, 812 (1978), and enclosed in Appendix B. The physical origin of the switching action is not understood yet. Preliminary results show, however, that the material can sustain current density of 160 kA/cm^2, which is a very positive factor.

APPENDIX A

List of Publications and Reports Resulting from this Grant

List of Publications and Reports Resulting From This Grant

1. E. A. Chauchard, M. J. Rhee, and Chi H. Lee, "Repetitive Opening Switches Using Optically Activated Semiconductors", 1985 Annual Meeting of the Optical Society of America, Oct. 14-18, 1985, Washington, D.C.

* 2. E. A. Chauchard, M. J. Rhee, and Chi H. Lee, "Optically Activated Semiconductors as Repetitive Opening Switches". Appl. Phys. Lett., 47, 1293 (1985).

3. M. J. Rhee, E. A. Chauchard, C. C. Kung, Chi H. Lee, and V. Diadiuk, "Fast Square Pulse Generation by an Optoelectronic Opening Switch and a Current Charged Transmission Line", IEEE Conf. Record-Abstract, 1986 IEEE Int. Conf. on Plasma Science, P. 24, Saskatoon, Canada, May 19-21, 1986.

4. E. A. Chauchard, C. C. Kung, M. J. Rhee, Chi H. Lee, and V. Diadiuk, "Repetitive Optoelectronic Opening Switch for Current Charged Transmission Lines", Conference on Lasers and Electrooptics, June 9-13, 1986, San Francisco, CA.

* 5. E. A. Chauchard, C. C. Kung, M. J. Rhee, Chi H. Lee, and V. Diadiuk, "A New Method to Generate Square Pulses: Optoelectronic Switching in a Current Charged Transmission Line', IEEE Transactions on Plasma Science, PS-15, 70 (1987).

* 6. E. A. Chauchard, Chi H. Lee, C. Y. Huang and A. M. Malvezzi "Graphite as a Picosecond Laser Activated Opening Switch", Conference on Picosecnd Electronics and Optoelectronics, Jan. 14-16, 1987, Lake Tahoe, NV.

7. E. A. Chauchard, C. C. Kung, Chi H. Lee, and C. Y. Huang, "Laser Induced Conductivity Drop in Graphite", Conference on Laser and Electronics, April 27 - May 1, 1987, Baltimore, MD.

* 8. E. A. Chauchard, Chi H. Lee, and C. Y. Huang, "Graphite Picosecond Optoelectronic Opening Switch", Appl. Phys. Lett. 50, 812 (1987).

* 9. E. A. Chauchard, C. C. Kung, Chi H. Lee, M. J. Rhee, and C. Y. Huang, "Two New Laser Activated Opening Switches", 1987 Int. Conf. on Lasers, Nov. 5-9, 1987, Xiamen, P.R. China.

10. E. A. Chauchard, C. C. Kung, Chi H. Lee, and C. Y. Huang, "Pulsed Laser Irradiation of Highly Oriented Pyrolytic Graphite", Bull. Am. Phys. Soc. 32, 608 (1987).

*11. E. A. Chauchard, C. C. Kung, Chi H Lee, and C. Y. Huang, "Demonstration of a Graphite Laser Activated Opening Switch", 1987 Pulsed Power Conf., June 29 - July 1, 1987. Arlington, VA.

*12. E. A. Chauchard, C. C. Kung, Chi H. Lee, and M. J. Rhee, "Repetitive Semiconductor Opening Switch and Application to Short Pulse Generation", submitted to the Laser and Particle Beams for publication.

* Included in Appendix B

APPENDIX B

Copies of Papers Published and Submitted

During the Period September 1, 1984 to August 31, 1987

Optically activated semiconductors as repetitive opening switches

E. A. Chauchard, M. J. Rhee, and Chi H. Lee
Electrical Engineering Department, University of Maryland, College Park, Maryland 20742

(Received 17 July 1985; accepted for publication 30 September 1985)

We demonstrate for the first time the operation of a semiconductor repetitive opening switch. A semiconductor is maintained in a conductive state by illumination with a cw argon laser light. The opening of the switch is obtained by interrupting the light. A turn-off time of 1 ns has been achieved.

The rapid progress of inductive energy storage circuits as pulsed power systems has required the development of new opening switches.[1-3] These switches should be fast, capable of handling high voltages, and, in many applications, jitter free. Among the switches commonly being used, many have the following drawbacks: slow turn-off time (100 ns–50 μs), single-shot operation, short closing period (50 ns–10 μs), low repetition rate (< 1 kHz), inaccurate triggering. The unique characteristics of light-activated solid-state switches make them prime candidates for repetitive opening switches. Since the switch is activated by a laser using the photoconductive effect, it is jitter free. Using bulk semiconductors, these switches can withstand high voltages and high current, as it has already been demonstrated for closing switches.[4,5] In this letter we demonstrate for the first time the operation of semiconductor opening switches, and we show that the turn-off time can be as fast as 1 ns.

In this work, two planar switches are examined. The two gold electrodes are deposited on the surface of a semiconductor wafer. One device is a 200-μm gap on bulk GaAs and the other is an interdigitated 4-μm gap on InGaAs:Fe. To keep the switch closed, its gap is continuously illuminated with argon laser light at 514 nm. The opening is achieved by interrupting the light by means of a Pockels cell placed between two parallel polarizers (Fig. 1). The electrical pulse delivered to the Pockels cell is 200 ns long; its rise time and fall time are <1 ns. To demonstrate the operation of the opening switch, we use an inductive storage circuit as shown in Fig. 1. The circuit is built in a shielded box to avoid the electromagnetic interference from the Pockels cell power supply. The temporal shape of the transient signal obtained when the switch opens is observed on the oscilloscope using a 50-Ω plug-in.

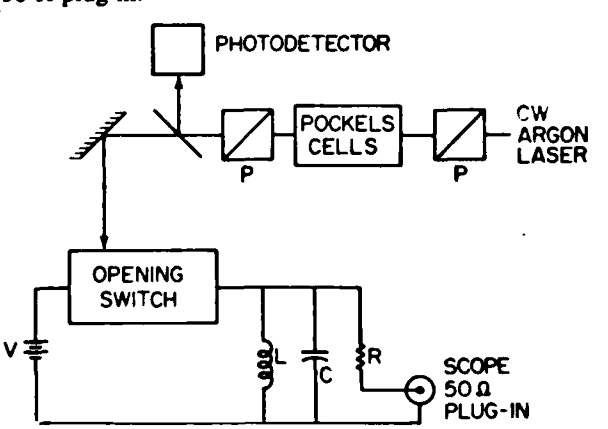

FIG. 1. Experimental setup. *P* is a polarizer.

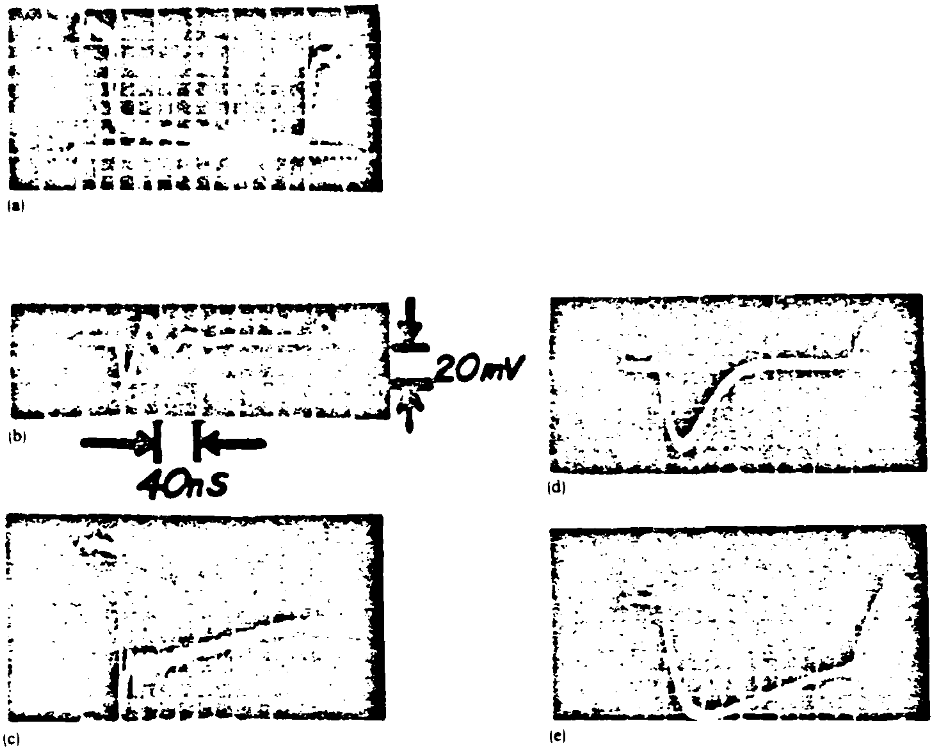

FIG. 2. Measured waveforms. (a) 200-ns-long cutoff of the light. (b)–(e) output voltage waveforms obtained with the GaAs switch for $V = 20$ V, $R_{on} = 12.5$ kΩ, and $R_{off} = 85$ kΩ. No capacitance was used. (b) $R_L = 573$ Ω, $L = 1.8\ \mu$H; (c) $R_L = 50$ Ω, $L = 20\ \mu$H; (d) $R_L = 573$ Ω, $L = 20\ \mu$H; (e) $R_L = 573$ Ω, $L = 156\ \mu$H.

In the circuit represented in Fig. 1, the current $I(t)$ through the load as the switch opens may be described by the following equation:

$$C\frac{d^2I(t)}{dt^2} + \frac{1}{R_L}\frac{dI(t)}{dt} + \frac{1}{L}I(t) = 0, \tag{1}$$

where C is the capacitance, L is the inductance, and R_L is the load resistance ($R_L = R + 50\ \Omega$). The solution of this equation with initial current I_0 at $t = 0$ is

$$I(t) = kI_0[\exp(S_1 t) - \exp(S_2 t)], \tag{2}$$

where $k = (2R_L C\sqrt{\Delta})^{-1}$, $S_1 = -(1/2R_L C) + \sqrt{\Delta}$, $S_2 = -(1/2R_L C) - \sqrt{\Delta}$, and $\Delta = (1/2R_L C)^2 - 1/LC$. I_0 in this case represents the amplitude of the current difference in the switch when it opens: $I_0 = V(1/R_{on} - 1/R_{off})$, where V is the applied voltage and R_{on} and R_{off} are the switch resistances at the on state and the off state, respectively. The waveforms described by Eq. (2) are of three types: Δ positive corresponds to overdamped solutions, Δ negative to oscillatory solutions, and $\Delta = 0$ corresponds to the critical damping. One can calculate the following features of the current waveforms. In the oscillatory case, the period of oscillation is

$$T = 2\pi/\sqrt{-\Delta}. \tag{3}$$

In the damped case, the slope of the current waveform at $t = 0$ is

$$\frac{dI}{dt} = \frac{I_0}{R_L C}, \tag{4}$$

and the fall time for the overdamped case is

$$\tau = (1/2R_L C - 1/\sqrt{\Delta})^{-1}. \tag{5}$$

If no capacitance is used in the circuit, a similar treatment leads to a fall time of

$$\tau = L/R_L. \tag{6}$$

The voltage signal observed on the oscilloscope is $u(t) = 50\times I(t)$.

The dark (off) resistances of the GaAs and InGaAs:Fe switches, respectively, are 2 MΩ and 150 kΩ. When illuminated with a 2-W argon laser beam focused on the gap, their resistances decrease to 10 kΩ and 150 Ω. Figure 2 shows the 200-ns-long cutoff of the light and the waveforms observed with the GaAs switch for different parameters of the circuit during the 200-ns period. No capacitance is used. To understand those waveforms for the values of V, R, L, R_{on}, and R_{off} given, one must take into account the stray capacitances of the circuit. Part of it (9.7 pF) is due to the 10-cm semirigid 50-Ω coaxial cable connecting the switch to the circuit. For the oscillatory case [Fig. 2(b)], Eq. (3) allows us to deduce a value of 22 pF for the capacitance. In the overdamped cases [Figs. 2(c), 2(d), and 2(e)], the fall time of the signal is in good agreement with Eq. (6), which holds if the capacitance is very small. Equation (4) allows us to calculate a value of the capacitance of 30 pF in Fig. 2(e), where the slope of the rising current at $t = 0$ can be easily measured. This value implies a fall time $\tau = 260$ ns, in good agreement with the measured value. The fastest rise time observed with the GaAs switch was 5 ns [Fig. 2(c)]. This is in accordance with the expected carrier recombination time in this undoped material. In the case of the InGaAs:Fe switch, the carrier recombination time is only of the order of 300 ps. The switch turn-off speed is then limited by the Pockels cell rise time (1 ns). We indeed observe a 1-ns turn-off time (Fig. 3). The waveforms obtained with the second switch show the same characteristics as those with the GaAs switch. In the experiment, no attempt has been made to further decrease

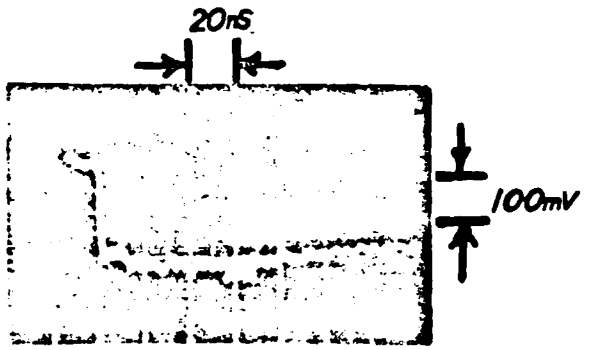

FIG. 3. Output voltage waveform obtained with the InGaAs:Fe switch for $R_L = 50\ \Omega$ and $L = 20\ \mu H$ showing a 1-ns rise time.

the resistance of the switches at the on state. This can be achieved by using higher laser power or longer wavelength. Indeed, the absorption depth of 514 nm wavelength light in GaAs is only 0.1 μm.[6] This is not suitable for obtaining a low on-state resistance, since it reduces the electron penetration depth to a very thin layer. Another development of these switches would be to use larger gap sizes capable of withstanding higher voltages.

In conclusion, we have demonstrated for the first time the operation of a 1-ns rise time semiconductor repetitive opening switch. Although in this work only 10 Hz repetition rates have been achieved, these switches are potentially capable of operating at very high repetition rates.

We wish to acknowledge V. Diadiuk from the MIT Lincoln Laboratory for supplying the InGaAs:Fe switch, and A. Rosen of RCA for suppling the GaAs switch. This work was supported by the Air Force Office of Scientific Research.

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A New Method to Generate Square Pulses: Optoelectronic Switching in a Current Charged Transmission Line

E. A. Chauchard
C. C. Kung
C. H. Lee
M. J. Rhee
V. Diadiuk

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A New Method to Generate Square Pulses: Optoelectronic Switching in a Current Charged Transmission Line

E. A. CHAUCHARD, C. C. KUNG, CHI H. LEE, MEMBER, IEEE, M. J. RHEE, MEMBER, IEEE, AND V. DIADIUK

***Abstract*—We demonstrated for the first time the operation of a new technique to generate square pulses of nanosecond duration at a 10-Hz repetition rate. This technique utilizes a current charged transmission line as an inductive storage element and a repetitive optoelectronic opening switch.**

I. Introduction

The development of pulsed power technologies has evolved steadily over the past two decades [1]. Of particular interest is the recent progress of inductive energy storage which allows a considerable reduction in the size of a system because its energy density is much higher than that of conventional capacitive storage. Thus the opening switch, by which the magnetic energy stored is released to a load, has recently been the subject of intense investigation [2]. It has been proposed [3], [4] that by using a current charged transmission line (CCTL) as an inductive storage and an opening switch one can produce a square pulse. This new transmission line configuration presents the compactness characteristic of inductive storage systems. There is no intrinsic limit on the pulse duration; however, the lower limit is determined by the switch opening time. It is thus of interest that repetitive operation of a light-activated semiconductor opening switch with nanosecond opening time has been demonstrated in our laboratory [5], [6]. In this note, we report the first experimental result of repetitive square pulse generation by employing the CCTL and the optoelectronic opening switch.

II. Current Charged Transmission Line Technique

The schematic circuit for the generation of square pulses is given in Fig. 1. When the switch is closed, electromagnetic energy in the form of magnetic field is stored in the transmission line. As the switch suddenly opens, the energy stored is transferred to the load. According to the CCTL theory, a total reflection occurs at the end of the shorted transmission line, and no reflection occurs at the load provided that its impedance is matched to that of the transmission line. A square pulse is then obtained with a duration equal to the round-trip time of the electromagnetic wave in the CCTL. A 6-m-long RG 58 cable providing a 60-ns pulse has been used as the CCTL in most of these experiments. One advantage of this technique is that the rise time of the pulse is limited only by the opening speed of the switch, as in the case of a charged transmission line with closing switch.

As described in previous reports [5], [6], the semiconductor switches used in this work are of planar geometry: two gold electrodes are deposited on the surface of the wafer. The different materials and gap geometries used are described in Table I. To keep the switch closed, its gap is continuously illuminated with argon laser light at 514 nm. The switch opening is achieved by interrupting the light by means of a Pockels cell placed between two parallel polarizers. The switch turn-off time is determined by the Pockels cell rise time (1 ns) or by the carrier recombination time in the semiconductor, whichever is slower. The amount of current in the CCTL is limited by the switch resistance in the conductive state and the bias voltage: $I = V/R_{on}$. To avoid excessive heating of the switch, the duty cycle is reduced by mechanically chopping the light at 10 Hz.

III. Testing of the Switches

The resistance of the switches as a function of CW argon laser power has been measured at a fixed bias voltage (Fig. 2). This resistance is given by the relation: $R \propto l^2/\mu Ne$, where N is the number of carriers per cubic centimeter, e is the charge of the electron, μ is the mobility of the carriers, and l is the length of the gap. In a first approximation where N is proportional to the laser power, this relation would lead to a slope of -1. This slope actually varies between -0.45 and -1.0. Possible explanations for this discrepancy are the saturation of the switch by the light, or a decrease of the carrier's recombination time at larger N values via Auger recombination or surface recombination, or a decrease of the carrier's

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V. Diadiuk is with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02173-0073.

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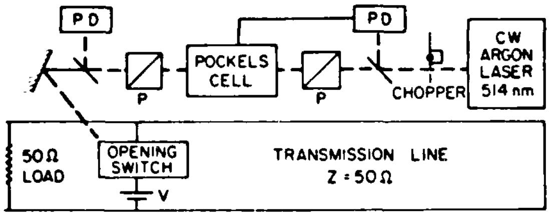

Fig. 1. Experimental setup.

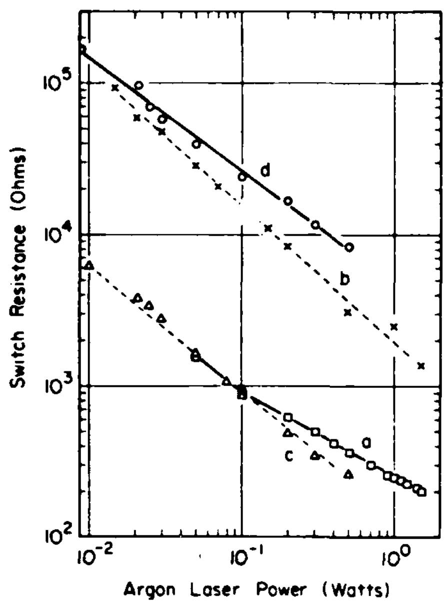

Fig. 2. Switch resistance as a function of the argon laser CW power. *a*—Switch 1 with bias voltage 2 V. *b*—Switch 2 with 2.6 V. *c*—Switch 3 with 2 V. *d*—Switch 4 with 0.7 V.

TABLE I
DESCRIPTION OF THE FOUR SWITCHES USED

Switch ID	material	gap size	gap geometry
1	GaAs	21 μm	single gap
2	Cr:GaAs	30 μm	single gap
3	Fe:InGaAs	3 μm	single gap
4	Fe:InGaAs	6 μm	interdigitated

mobility at high carrier densities due to carrier-carrier scattering [7]. Because of the following two difficulties, these curves do not represent a complete study of the switch behavior. First, the *I-V* curves of these devices show some nonlinearity indicating that the resistance is dependent on the bias voltage. Second, the resistance varies slightly with the position of the laser illumination in the gap. These curves indicate that the argon laser light is not very efficient at lowering the on-resistance of the switches. This is expected because the power of this CW laser is insufficient and because the penetration depth of the 514-nm light in GaAs and InGaAs is only 0.1 μm, resulting in a very shallow layer of electron-hole plasma.

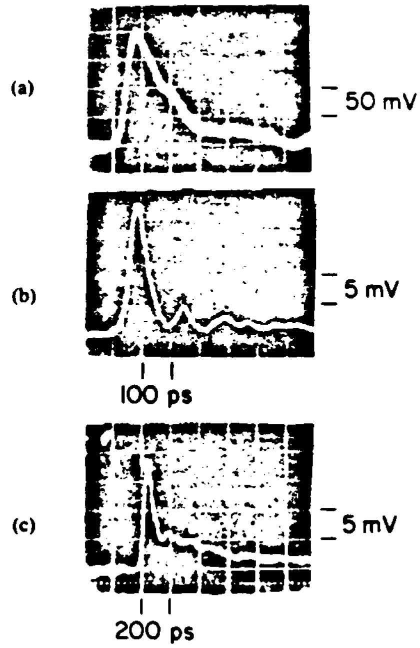

Fig. 3. Response of switches in closing switch configuration. (a) Switch 2. (b) Switch 3. (c) Switch 4.

The switches have also been tested in the closing switch configuration in order to determine their recovery time. For this purpose, a GaAs diode laser emitting 50-ps pulses at 860 nm and a CW mode locked dye laser emitting 6-ps pulses at 590 nm have been used. The results given in Fig. 3 show a 100-ps recombination time for one of the Fe:InGaAs switches. The other Fe:InGaAs switch presents a two-component decay time. The first component is 100 ps long, the second one is slower (≃ 1 ns). The Cr:GaAs switch shows a 200-ps recombination time.

IV. Results and Discussion

The square pulses obtained with several switches are shown in Fig. 4. The slightly noisy appearance of the leading edge of the pulses is explained by large Argon laser mode fluctuations observed at a frequency of 100 MHz corresponding to its cavity length. The fastest rise time is obtained with the Cr:GaAs switch and one of the InGaAs switches (1.5 ns). When these switches were used, the limiting factor for the opening time was found to be the rise time of the Pockels cell (1 ns). Only in the case of the GaAs switch, the opening time is limited by the material carrier recombination time, as expected for this undoped material. The interdigitated Fe:InGaAs switch is found to be unsuitable for 10-Hz operation: the heat accumulation causes the density of carriers to increase continuously over several minutes while the carrier recombination time is degraded down to 10 ns. For this reason, the result shown in Fig. 4(d) for this switch is obtained in single-pulse conditions. When assessing the efficiency of the system, two factors have to be taken into

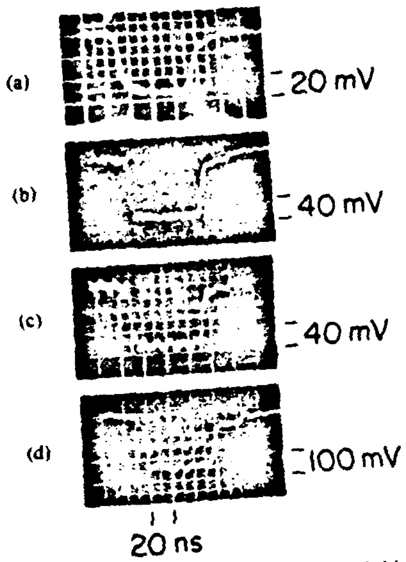

Fig. 4. Square pulses obtained with: (a) switch 1 with bias voltage 5 V; (b) switch 2 with 15 V; (c) switch 3 with 4 V; and (d) switch 4 with 2 V.

consideration: 1) the energy transfer from the CCTL to the load which was studied in terms of the ratio of the output energy to the stored energy in the CCTL and was found to be close to 100 percent; and 2) the amplitude of the current charged in the CCTL which is given for a given bias voltage by the switch on-resistance. This is the limiting factor of the system efficiency. Further decreasing the on-resistance is rather difficult to achieve with the argon laser since the optically induced layer of electron-hole plasma is too thin to produce low resistance. Future experiments will be conducted with a pulsed infrared laser.

In conclusion, generation of very fast rise-time and fall-time square pulses using a current charged transmission line and an optoelectronic opening switch was demonstrated. Although in this experiment only 10-Hz operation has been realized (limited by the Pockels cell circuit), much higher repetition rates are possible in principle. In the closing switch configuration, it has already been demonstrated that larger gap bulk semiconductor switches can sustain very high voltages and currents [8]. In the same manner, the technique described in this work can be scaled to high-voltage/high-current systems provided that the switch material, the light source wavelength, and power are matched.

Acknowledgment

The authors wish to acknowledge A. Rosen of RCA for supplying the GaAs switches.

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Graphite picosecond optoelectronic opening switch

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Highly oriented pyrolytic graphite, a conductive material in the dark, is found to exhibit a high resistivity when illuminated by intense laser light. Its operation as an opening switch with a switching time under 1 ns is demonstrated.

In a recent experiment, Huang *et al.*[1] have investigated semimetallic layered highly oriented pyrolytic graphite (HOPG). They have observed a sudden decrease in the reflectivity as the sample is illuminated by an intense picosecond laser pulse when the fluence is above the threshold of 140 mJ/cm^2 at 566 nm. This unexpected result indicates that a phase transformation occurs and that the high-temperature phase, which they believe to be liquid, is nonmetallic. This experimental observation is consistent with the result of the recent pseudopotential calculation that there is an energy gap in "isotropic" carbon.[2] These authors also report the appearance of a permanent damage black ring on the surface of the sample when the irradiation is above the melting threshold, which provides evidence for the structural transformation. The time-resolved experiments[1] show that the phase transformation is completed in time scales as short as ~ 10 ps and that the new phase lasts for approximately 3 ns. In the work presented here, we directly assess the change of resistivity of a HOPG sample used as a laser activated switch. We confirm the results reported in Ref. 1 by observing a large increase in the sample's resistivity under intense picosecond laser illumination. This unique property could allow one to use graphite as an opening switch since it is a semimetal in the "dark." Its conductivity in the *c* plane in the dark state [$\sigma = 0.25\times 10^5$ $(\Omega\ \text{cm})^{-1}$] is almost as good as that of pure copper. It could then be compared to semiconductor optoelectronic switches, noting that its operation is exactly inverse: it is conductive in the dark and its resistance increases when illuminated above the threshold. The main application of this type of switch is in the pulse power technology where the recent interest for inductive storage systems has created a need for an efficient, repetitive, jitter-free opening switch.[3] In Refs. 4 and 5, we proposed to use a semiconductor material as opening switch and demonstrated that it is feasible. In this letter, we demonstrate that graphite is a suitable alternative material for opening switch applications with some advantages. To assess the possibility of using HOPG as a practical device, it is of great importance to measure the rate of the phase transition as well as that of its recovery. The technique used in Ref. 1 only allows us to perform these measurements at the surface of the sample. Here, we directly study the opening speed of the HOPG switch which is equal to the response time for the phase transition and find the best opening speed to be less than 1 ns.

To demonstrate the operation of HOPG as opening switch, a circuit configuration of current transmission line as described in Ref. 4 was used (Fig. 1). In this type of circuit, the energy is stored in the magnetic form in a transmission line of impedance 50 Ω. As the switch opens and remains open the current flows towards the 50-Ω load of the oscilloscope and a square pulse is observed. If the switch is ideal (infinite resistance in the open state), the current flowing towards the load is one-half of the charging current and the totality of the energy stored in the transmission line is transferred to the load. This ideal case defines 100% switching efficiency. The duration of the square pulse (30 ns) is determined by the length of the transmission line (3 m). The rise and fall times of the square pulse are equal to the switch opening time. A *Q*-switched mode-locked Nd:YAG laser, providing 30 ps pulses at 1.06 μm, was used to illuminate the HOPG sample.

The switch was fabricated in a thin (4–6 μm) sheet of material which can be easily pealed off from the HOPG block. This sheet is parallel to the *c* plane. A narrow slab of 50–150 μm is then cut, mounted on a piece of sapphire, and connected to microwave SMA connectors using silver epoxy. The typical switch resistance, including the contact resistances, was approximately 10 Ω. The small dimensions of the sample are required for the following reason. In order to observe a significant change of resistivity by the method described here, the total sample cross section needs to undergo the phase transformation. The sample thickness should thus be no larger than a few times the linear optical penetration

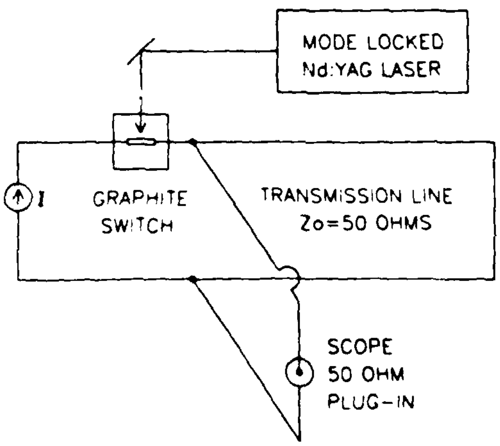

FIG. 1. Experimental setup for the generation of square pulses using a laser activated opening switch and a current charged transmission line.

depth which is only 0.04 μm for the 1.06 μm light used. We found that this difficulty can be overcome by using the high energy laser pulses to etch the sample surface until a suitable thickness is reached and the signal starts being visible. Because of the high laser fluences used, it is likely that the actual penetration depth is larger than 0.04 μm: the first molten layer formed is more transparent and allows the light to penetrate deeper.

The waveforms shown in Figs. 2 and 3 indicate that the opening switch action was obtained. It was found as in Ref. 1 that a high laser fluence is necessary to obtain this result (> 140 mJ/cm^2). The shape of the electrical pulse obtained was not reproducible from shot to shot or from sample to sample. The fastest speed observed on Fig. 2(a) was less than 1 ns (oscilloscope limited). The switching efficiency was quite high: 90%, corresponding to a resistance of the sample of 450 Ω after illumination. A square pulse may be obtained only if the duration of the "open" state of the switch is larger than the round-trip propagation time in the transmission line. The results shown in Fig. 2 thus indicate that the open state can last over 30 ns which is in disagreement with the value of ~ 3 ns given in Ref. 1. This may be due to the fact that the measurements reported in Ref. 1 were only probing the sample's surface which is likely to recover faster than the bulk. Figure 3 is an example of waveform obtained when the switching efficiency is low, the resistance of the sample in the open state being only 56 Ω. In this case, only a small part (6%) of the energy contained in the transmission line is transferred to the load, the largest part being reflected back in the transmission line. The successive pulses observed correspond to the successive reflections of the wave in the transmission line. A higher fluence than in Fig. 2 was necessary to obtain the switching action, indicating that the sample was thicker. In the case of low efficiency switching as in Fig. 3, the waveforms obtained were quite reproducible from shot to shot. The rate of decay of the successive pulses can give a measurement of the closing speed of the switch which is directly related to the disappearance of the new phase. This measurement can also be performed without the transmission line configuration. In both cases, a decay time of the order of 100 ns was found. In the case of high efficiency switching, an observation at longer time scales often revealed the occurrence of several irregular pulses separated by hundreds of nanoseconds. This fact has not been explained.

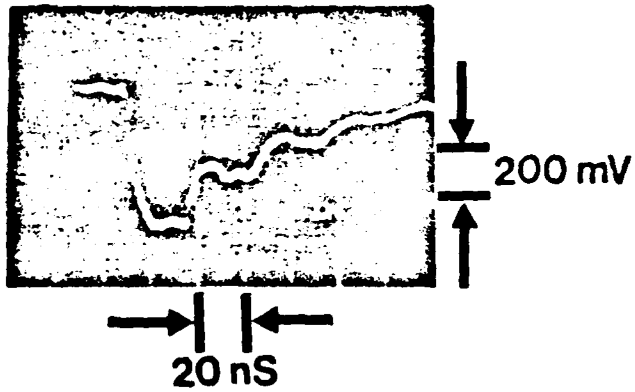

FIG. 3. Example of waveform generated in a case of low switching efficiency. The laser pulse energy was 0.90 mJ and the charging current 400 mA.

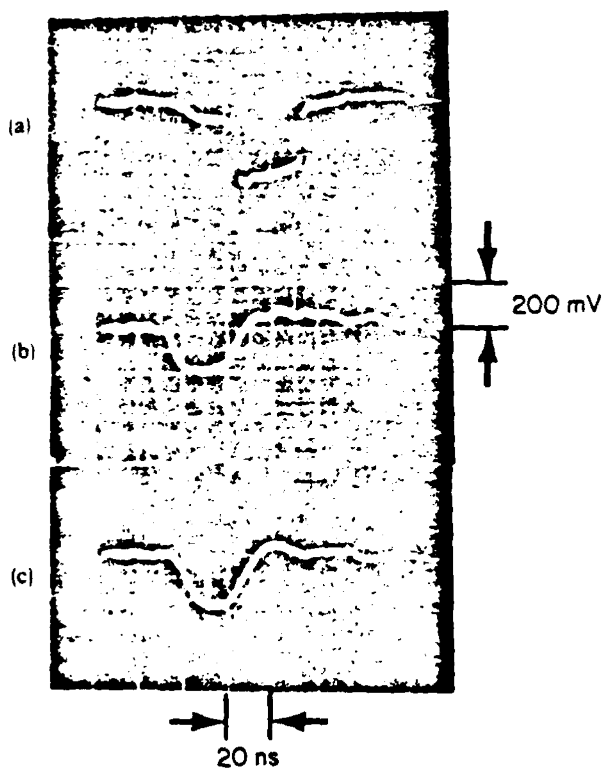

FIG. 2. Three examples of waveforms generated as the graphite switch opens. Each trace was obtained with a different laser pulse but the sample of graphite was the same. The laser pulse energy was (a) 0.16 mJ, (b) 0.14 mJ, and (c) 0.16 mJ. The charging current was 16 mA.

The maximum dc current in the c plane that the sample can sustain was estimated to be 160 kA/cm^2. The lack of reproducibility observed in the high efficiency switching case shows that it is difficult to control the formation of the liquid phase and its decay. Part of this irreproducibility can also be attributed to the fluctuations of the laser intensity and mode pattern. Although it is reported in Ref. 1 that the new phase is liquid, these first experiments do not allow us to accurately identify its nature. A better understanding of the new phase would certainly allow us to better determine the switching parameters. Further research is necessary in this direction.

The subnanosecond opening speed, the fact that the switching efficiency of this material can be very good, and the fact that it can sustain a high current density make it a very promising candidate for opening switch applications. From a more fundamental point of view, it is of particular interest to note that HOPG is, to our knowledge, the only material exhibiting this type of behavior.

We are grateful to Professor N. Bloembergen and Dr. A. M. Malvezzi for many stimulating discussions. We would also like to thank Professor M. L. Cohen for sending his paper prior to publication. One of us (CYH) is supported by the U.S. Department of Energy. This work was supported by the Air Force Office for Scientific Research.

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Graphite as a Picosecond Laser Activated Opening Switch

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In a recent experiment, Malvezzi et al. have observed a large decrease in the reflectivity of a semimetallic sample of highly oriented pyrolytic graphite (HOPG) as it is illuminated by an intense picosecond laser pulse when the fluence is above the melting threshold. They have found that the imaginary part of the refactive index reaches lower than ≈0.5 at 566 nm [1]. This unexpected result indicates that a phase transformation occurs and that the high temperature phase, which they believe to be liquid, is non-metallic. This experimental observation is consistent with the result of the recent pseudo-potential calculation that there is an energy gap in "isotropic" carbon [2]. The time resolved experiments [1] also show that the phase transformation is completed in time scales as short as ~10 ps. In the work presented here, we directly assess the change of resistivity of a HOPG sample used as a laser activated switch. We confirm the results reported in [1] by observing a large increase in the sample's resistivity under intense picosecond laser illumination. This unique property could allow one to use graphite as an opening switch since it is a semi-metal. Its conductivity in the dark state (≈.25 10^5 $(\text{ohm.cm})^{-1}$) is almost as good as that of pure copper. It could then be compared to semiconductor optoelectronic switches, noting that its operation is exactly inverse: it is conductive in the dark and its resistance increases when illuminated above t[illegible] threshold. T[illegible] pulse power technology where the recent interest for inductive storage systems has created a need for an efficient, repetitive, jitter free opening switch [3]. In [4,5], we proposed to use a semiconductor material as opening switch and demonstrated that it is feasible. In this paper, we demonstrate that graphite is a suitable alternate material for opening switch applications with some advantages. To assess the possibility of using HOPG as a practical device, it is of great importance to measure the speed of the phase transition as well as the speed of its recovery. The technique used in [1] only allows to perform these measurements at the surface of the sample. Here, we directly study the opening speed of the HOPG switch which is equal to the response time for the phase transition and

find the best opening speed to be less than one nanosecond.

To demonstrate the operation of HOPG as opening switch, a circuit configuration of current charged transmission line as described in [4] was used (Fig. 1). In this type of circuit, the energy is stored under magnetic form in a transmission line and a square pulse is generated when the switch opens. The duration of the square pulse (30ns) is determined by the length of the transmission line (3m). The rise and fall time of the square pulse are equal to the switch opening time. A Q-switch mode-locked Nd:YAG, providing 30ps pulses at 1.06μm was used to illuminate the HOPG sample. The waveforms shown in Fig. 2 indicate that the opening switch action was obtained. It was found as in [1] that a high laser fluence is necessary to obtain this result (>140 mJ/cm^2). The opening time was not reproducible from shot to shot; the fastest speed was less than 1 ns (oscilloscope limited). The maximum DC current in the c-plane that the sample can sustain was estimated to be 160 kA/cm^2. The switching efficiency was quite high: 90%, corresponding to a resistance of the sample of 450 ohms after illumination. The lack of reproducibility is attributed to the fact that the laser intensity and mode pattern were fluctuating. One other difficulty was that the thickness of the HOPG sample was not controlled. This is a determining factor since, for the opening action to be optimum, it is necessary that the total sample cross-section illuminated by the laser pulse undergoes the phase transformation. Although it is reported in [1] that the new phase is probably liquid, these first experiments do not allow to accurately identify its nature. A better understanding of the new phase would certainly allow us to better determine the switching parameters. Further research is necessary in this direction.

The subnanosecond opening speed, the fact that the switching efficiency of this material is quite good, and the fact that it can sustain a high current density make it a very promising candidate for opening switch applications. From a more fundamental point of view, it is of particular interest to note that HOPG is, to our knowledge, the only material exhibiting this type of behavior.

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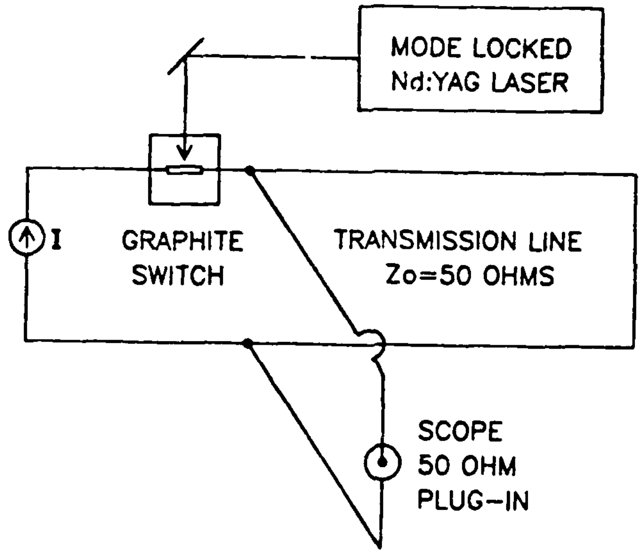

Fig. 1: Experimental set-up for the generation of square pulses using a laser activated switch and a current charged transmission line.

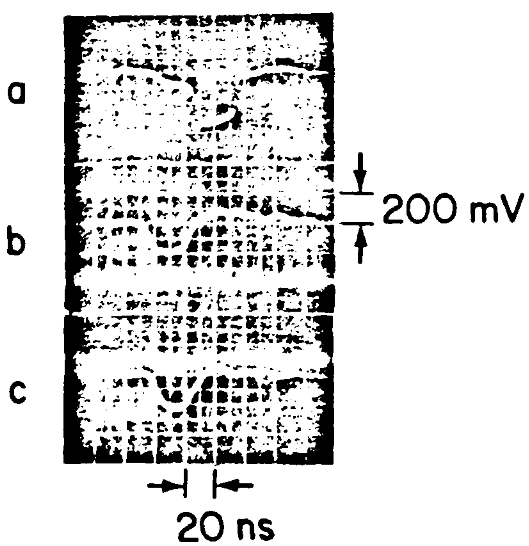

Fig. 2: Three examples of waveforms generated as the graphite switch opens. Each trace is obtained with a different laser pulse but the sample of graphite is the same. The laser pulse energy is: a: 0.15 mJ, b: 0.14 mJ, c: 0.16 mJ.

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Demonstration of a Graphite Laser Activated Opening Switch

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Highly Oriented Pyrolytic Graphite, a conductive material in the dark, was found to exhibit a high resistivity when illuminated by intense laser light. This unique property makes it a suitable material for opening switch applications. Its operation as an opening switch with a switching efficiency of 90 percent was demonstrated. Switching to the high resistivity state occurs in picoseconds and the switch recovers its original conductivity in less than 10 μs. In the absence of laser irradiation, the graphite sample can sustain a current density as high as 160 kA/cm^2. The switching action is probably due to a phase transformation of the graphite sample. Because the laser fluence required to induce this phase transformation is quite high (140 mJ/cm^2), the switch dimensions had to be kept small. The repetitivity of the opening switch was established by obtaining several hundreds of switchings with the same graphite sample.

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In a recent experiment, Huang et al. [1] investigated semimetallic layered highly oriented pyrolytic graphite (HOPG). They observed a sudden decrease in the reflectivity as the sample is illuminated by an intense picosecond laser pulse when the fluence is above the threshold of 140 mJ/cm^2 at 566 nm. This unexpected result indicates that a phase transformation occurs and that the high temperature phase is non-metallic. The time resolved experiments [1] show that the phase transformation is completed in time scales as short as ~10 ps. In the work presented here, we directly assess the change of resistivity of a HOPG sample used as a laser activated switch. We observe a large increase in the sample's resistivity under intense picosecond laser illumination. This unique property allows to use graphite as an opening switch since its conductivity in the c-plane in the dark state (σ=0.25 $10^5(\mathrm{ohm}\cdot\mathrm{cm})^{-1}$) is almost as good as that of pure copper. The main application of this type of switch is in the pulse power technology where the recent interest for inductive storage systems has created a need for an efficient, repetitive, jitter free opening switch. In [2], we proposed to use a semiconductor material as opening switch and demonstrated that it is feasible. In this paper, we demonstrate that graphite is a suitable alternate material for opening switch applications with some advantages.

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The waveforms shown in Fig.1 indicate that the opening switch action was obtained. The shape of the electrical pulse obtained was not reproducible from shot to shot or from sample to sample. The fastest speed obsereved on Fig.1a was less than 1 ns (oscilloscope limited). The

switching efficiency was quite high: 90 percent, corresponding to a resistance of the sample of 450 ohms after illumination. The switch recovery time varied with the laser intensity. In cases of low laser intensity, where the observed waveforms were reproducible, a recovery time of ~150 ns was observed. In cases of high laser intensity, corresponding to high switching efficiencies as in Fig. 1, the recovery time was up to 10 μs. The maximum DC current density in the c-plane that the sample can sustain was estimated to be 160 kA/cm^2. The lack of reproducibility observed in the high efficiency switching case shows that it is difficult to control the formation of the liquid phase and its decay. Part of this irreproducibility can also be attributed to the fluctuations of the laser intensity and mode pattern.

The subnanosecond opening speed, the fact that the switching efficiency of this material can be very good, and the fact that it can sustain a high current density make it a very promising candidate for opening switch applications. From a more fundamental point of view, it is of particular interest to note that HOPG is, to our knowledge, the only material exhibiting this type of behaviour.

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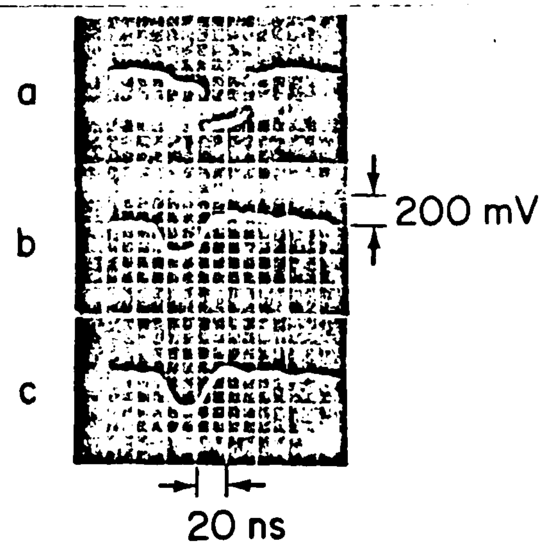

Fig. 1: Three examples of waveforms generated as the graphite switch opens. Each trace is obtained with a different laser pulse but the sample of graphite is the same. The laser pulse energy is: a: 0.16 mJ, b: 0.14 mJ, c: 0.16 mJ. The charging current is 16 mA.

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Two New Laser Activated Opening Switches

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ABSTRACT

Two repetitive opening switches are demonstrated. One uses a semiconductor which is maintained in the conducting state by laser illumination and opened by interrupting the light. The other uses a conductive graphite which exhibits conductivity drops by laser illumination.

Two New Laser Activated Opening Switches

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The rapid progress of inductive energy storage circuits as pulsed power systems has required the development of new opening switches [1]. The ideal switch should be fast, repetitive, capable of high repetition rate operation, and, for many applications, jitter free. We report on the experimental implementation of two laser activated switches which can fulfill these requirements.

The first type of device is a photoconductive semiconductor switch fabricated by deposition of two gold electrodes on the surface of the waver. GaAs, Cr:GaAs, and Fe:InGaAs have been used. To keep the switch in the closed state, its gap is continuously illuminated with argon laser light at 514 nm. The opening is achieved by interrupting the light by means of a Pockels cell placed between two parallel polarizers. The switch turn-off speed is given by the Pockels cell rise time (1 ns) or by the carrier recombination time in the semiconductor, whichever is slower. To demonstrate the operation of the switch, it was used with a current charged transmission line (CCTL) [2] to generate square pulses of 1 ns rise and fall time. When the switch is closed, electromagnetic energy in the form of magnetic field is stored in the transmission line. As the switch suddenly opens, the energy stored is transferred to the load. A square pulse is then obtained with a duration equal to the round trip time of the electromagnetic wave in the CCTL. One advantage of this technique is that the rise and fall times of the pulse are limited only by the opening speed of the switch.

The generation of 1 ns rise-time and fall-time square pulses was demonstrated. High repetition rates are in principle possible. The technique described in this work can be scaled to high voltage/high current systems provided that the switch material, and the light source wavelength and power are matched.

The second type of opening switch was made of semimetallic layered Highly Oriented Pyrolytic Graphite (HOPG). In a recent experiment, Huang et al. [3] have observed a sudden decrease in the reflectivity as the HOPG sample is illuminated by an intense picosecond laser pulse when the fluence is above the threshold of 140 mJ/cm^2 at 566 nm. This unexpected result indicates that a phase transformation occurs and that the high temperature phase, which they believe to be liquid, is non-metallic. The time resolved experiments [3] show that the phase transformation is completed in time scales as short as ~10 ps. Here, we directly assess the change of resistivity of a HOPG sample used as a laser activated switch. We confirm the results reported in [1] by observing a large increase in the sample's resistivity under intense picosecond laser illumination. This unique property allows the use of graphite as an opening switch since it is a semi-metal in the "dark." Its conductivity in the c-plane

in the dark state ($\sigma = 0.25\ 10^5 (\text{ohm.cm})^{-1}$) is almost as good as that of pure copper. A Q-switch mode-locked Nd:YAG laser, providing 30 ps pulses at 1.06 µm was used to illuminate the HOPG sample. The maximum DC current in the c-plane that the sample can sustain was estimated to be 160 kA/cm^2. The graphite opening switch was used in a CCTL circuit and square pulses of less than 1 ns rise and fall time (oscilloscope limited) could be generated. The rise and fall time of the pulses, however, were not reproducible and could be as long as 5 ns.

The subnanosecond opening speed, the fact that the switching efficiency of this material can be very good, and the fact that it can sustain a high current density make it a very promising candidate for opening switch applications. From a more fundamental point of view, it is of particular interest to note that HOPG is, to our knowledge, the only material exhibiting this type of behavior.

Acknowledgements

We are grateful to Professor N. Bloembergen and Dr. A. M. Malvezzi for many stimulating discussions on the graphite part of this work. We wish to acknowledge A. Rosen of RCA for supplying the GaAs switches and V. Diadiuk of MIT Lincoln Laboratories for supplying the InGaAs switches. On of us (CYH) is supported by the U.S. Department of Energy. This work was supported by the Air Force Office of Scientific Research.

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REPETITIVE SEMICONDUCTOR OPENING SWITCH AND APPLICATION TO SHORT PULSE GENERATION

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ABSTRACT

We describe the operation of a repetitive semiconductor opening switch in conjunction with inductive energy storage systems. Different materials and configurations of switches are examined. A new method of generating square pulses of nanosecond duration is implemented. It utilizes the opening switch and a current charged transmission line.

Introduction.

In the past two decades, pulsed power systems have been developed for numerous applications (Nation, 1979). They have mainly relied upon electrostatic energy storage used in capacitor banks, simple transmission lines or Blumlein lines. The electrostatic storage systems of high voltage requires a large structure and volume of insulating dielectric to hold off the charging voltage. In addition, if the voltage is higher than that attainable from a commonly available dc power supply (say, 100 kV), it requires a voltage step-up device such as a Marx generator, a Van de Graaff, or a high voltage transformer. Inductive storage systems can be operated at lower voltage and thus require neither a step-up device nor high voltage insulation (Schoenbach et al., 1984). For these reasons, they are much more compact and are gaining an advantage over the capacitive storage systems. The main difficulty, however, remains the opening switch which allows the inductive energy to be transferred to the load (Schoenbach et al., 1984; Meger et al., 1983). The development of a suitable opening switch in particular for the application to high power systems presents a number of challenges. The switch should have a fast opening time (ns) to allow a fast transfer of the energy to the load, and a fast recovery time in order to achieve high repetition rate operation. The duration of its conduction period must be sufficient to charge the circuit, its impedance after opening should be high, and its triggering should be accurate. Finally, the switch must be capable of conducting a high current and of holding a high voltage before and after the switch opening, respectively. The opening switches currently being used are mostly of single shot type (e.g., fuses, explosive driven switches). Among the drawbacks found in the existing repetitive switches are: slow repetition rate, short conduction period, slow opening time, and inaccurate triggering.

The unique characteristics of light activated solid state switches (Lee,

1984) make them prime candidates for a repetitive opening switch. Since the switch is activated by a laser light using the photoconductive effect, the accuracy of switching is up to the limit of laser jitter. Using bulk semiconductors, the switch may be configured to withstand a high voltage and high current as it has already been demonstrated for closing switch applications (Nunnally, 1985). Because of the picosecond response time of some semiconductor materials, very fast opening and very high repetition rates can, in principle, be achieved.

In this work, we demonstrated the operation of a semiconductor opening switch. Different materials and gap sizes were examined and the main issues were identified. We measured a turn-off time of 1 ns at a repetition rate of 10 Hz. We also report the first experimental implementation of a square pulse generation technique proposed in Glasoe et al., 1964, and Rhee et al., 1983. This technique uses a current charged transmission line (CCTL) coupled with an optoelectronic opening switch. As a proof-of-principle of this technique, square pulses with a rise time and a fall time of 1.5 ns were generated with a repetition rate of 10 Hz.

Description of the Opening Switch.

The operational principle of the semiconductor switch is based on the photoconductive effect. In the dark, the semiconductor is a good insulator. As light illuminates the semiconductor, an electron-hole plasma is generated, and it becomes a conductor. The semiconductor switches used in this work are of planar geometry: two gold electrodes are deposited on the surface of the semiconductor wafer. The different materials and gap geometries used are summarized in Table I. To keep the switch in a closed state, the gap was continuously illuminated with cw argon laser light at 514 nm (Chauchard et al., 1985a and b). The switch opening is achieved by interrupting the light by means of a Pockels cell placed between two parallel polarizers (Fig. 1). The electrical pulse

delivered to the Pockels cell was 200 ns (or 300 ns) long during which the switch is in the open state. To demonstrate a repetitive operation of the system, a 10 Hz mechanical chopper of duty cycle 30 percent was employed in front of the Pockels cell. The turn-on time of the semiconductor closing switch is simply as fast as the rise time of the laser since the generation of the electron-hole plasma is instantaneous. The turn-off time of the opening switch, however, is limited by two factors: the speed of interruption of the light, which in this case is given by the rise time (1 ns) of the Pockels cell, and the carrier recombination time in the material.

Demonstration of an Opening Switch Operation in a Lumped Inductive Storage System.

A lumped inductive storage circuit as shown in Fig. 1 was used to demonstrate the operation of the switch. The circuit was built in a shielded box to avoid the electromagnetic radiation noise from the Pockels cell power supply. In this circuit, the current I(t) through the load resistor after the opening of the switch can be described by the following equation:

$$C \frac{d^2 I(t)}{dt^2} + \frac{1}{R_L}\frac{dI(t)}{dt} + \frac{1}{L} I(t) = 0 \ , \tag{1}$$

where C is the capacitance, L is the inductance, and R_L is the load resistance ($R_L = R + 50$ ohm). The solution is readily found with initial conditions $I_{(0)} = I_o$ and $C\, dV/dt = I_o$ at $t = 0$ as,

$$I(t) = kI_o \left[\exp(S_1 t) - \exp(S_2 t)\right] \ , \tag{2}$$

where $k = (2R_L C\sqrt{\Delta})^{-1}$, $S_1 = -1/2R_L C + \sqrt{\Delta}$, $S_2 = -1/2R_L C - \sqrt{\Delta}$, and $\Delta = (1/2R_L C)^2 - 1/LC$. The waveforms described by eq. (2) are of three types: $\Delta > 0$ corresponds to the overdamped solution, $\Delta < 0$ to the oscillatory solution, and $\Delta = 0$ to the critical damping. One easily finds the following features of

the current waveforms. In the oscillatory case, the period of oscillation is

$$T = 2\pi/\sqrt{-\Delta} \; . \tag{3}$$

In the damped case, the slope of the current waveform at t = 0 is

$$\frac{dI}{dt} = \frac{I_0}{R_L C} \; , \tag{4}$$

and the fall time for the overdamped case is

$$\tau = \left(\frac{1}{2RC} - \sqrt{\Delta}\right)^{-1} \tag{5}$$

If no capacitance is used in the circuit, a similar treatment leads to a fall time of

$$\tau = L/R_L \; . \tag{6}$$

The voltage signal observed on the oscilloscope is: $u(t) = 50 \times I(t)$.

The dark (off) resistances of the GaAs and InGaAs:Fe switches, respectively #1 and #4 on Table I, are 2 MΩ and 150 kΩ. When they are illuminated with a 2 W argon laser beam focused on the gap, the resistances are decreased to 10 kΩ and 150 Ω, respectively.

Figure 2 shows a light intensity waveform monitored by a fast photodiode showing the 300 ns long cut-off by the Pockels cell. The contrast ratio of the Pockels cell was better than 200, assuring that there was very little residual light on the switch during its open state. Two examples of waveforms, oscillatory and overdamped cases, obtained with the GaAs switch (#1 on Table I) are shown in Fig. 3. The duration of the light cut-off was 200 ns long and no external capacitor was used. The observed waveforms are in good agreement with the calculated waveforms taking into account the stray capacitance of the circuit (≈ 30 pF). The fastest rise time obtained with this GaAs switch was 5 ns.

It was limited by the carriers recombination time in the material. In the case of the InGaAs:Fe (#4), the recombination time is approximately 200 ps. The switch turn-off speed was then limited by the rise time of the Pockels cell (1 ns). We observed a 1 ns turn-off time (Fig. 4). The maximum amplitudes of the signals were rather small compared to the power supply voltages because the argon laser light is not efficient at lowering the on-state resistance of the switch as explained in the next section.

Testing of the Semiconductor Switches.

The dc resistance of some of the switches as a function of cw argon laser power was measured at a fixed bias voltage and is plotted in Fig. 5. This resistance R is proportional to ($\ell/\mu N e$), where N is the number of carriers per cm^3, e is the charge of the electron, μ is the mobility of the carriers, ℓ is the length of the gap. In the first approximation in which N is assumed to be proportional to the laser power, the resistance vs. the laser power curve would have a slope of -1. For the curves represented in Fig. 5, this slope actually varies between -0.45 and -1. This discrepancy is attributed to the saturation of the switch. The saturation occurs through nonlinear recombination processes (Auger recombination or surface recombination) which imply a faster recombination time at larger carrier densities resulting in a smaller N value. Furthermore, the decrease of the carrier's mobility at high carrier densities due to carrier-carrier scattering may also be responsible. Because of the two following difficulties, these curves do not represent a complete study of the switch behavior. First, the I-V curves of these devices show some nonlinearity indicating that the resistance is dependent on the bias voltage. An example of I-V curve is shown in Fig. 6. Second, the resistance varies slightly with the position of the laser illumination in the gap. These curves indicate that the argon laser light was not very efficient at lowering the on-state resistance of

the switches. This was expected because the output power of this cw laser is insufficient and because the penetration depth of the 514 nm light in GaAs and InGaAs is only 0.1 μm (Sze, 1981), leading to the formation of a very shallow layer of electron-hole plasma. The scaling up of the experiment to a higher current switching requires a thicker conduction layer. For this reason, it is desirable to conduct future experiments with a pulsed IR laser.

To study the switching characteristics, the switches were tested conveniently in the closing switch configuration where the switch is inserted between a bias voltage source and a sampling scope of 25 ps rise time. A GaAs diode laser emitting 50 ps pulses at 0.86 μm and a cw mode-locked dye laser emitting 6 ps pulses at 0.59 μm were used. The results as shown in Fig. 7 show a 100 ps recombination time for both InGaAs:Fe switches. For one of them, a longer (1 ns) component of the fall time was observed. This longer decay time was found to increase as the bias voltage on the switch decreases (Fig. 8), indicating a "sweep-out" effect. The term sweep-out (Shahidi 1985) refers to the drift of the carriers towards the electrodes due to the electric field applied on them by the bias voltage. If a sufficiently high bias voltage (10 volts) is used, the long component of the switch response disappears and the device is suitable for the opening switch application. Another feature can be noted on Fig. 7: although 50 ohms SMA connectors have been used for mounting the switch, some reflections are visible. They are due to a mismatch at the connector junction to the device and represent a difficulty in the design of the switch. The variation of the switch response waveform with light intensity has also been studied (Fig. 9). It showed, in general, a saturation of the switch for which a possible explanation can be found in Ref. Li et al., 1982.

<u>Generation of Nanosecond Square Pulses</u>.

It has been proposed (Glasoe et al., 1964; Rhee et al., 1983) that by using

a current charged transmission line (CCTL) as an inductive storage, and an opening switch, one can produce a square pulse. Because the energy storage, is inductive, the compactness feature mentioned earlier is utilized in this technique. There is no intrinsic limit on the pulse duration; however, the lower limit may be mainly determined by the switch opening time (Chauchard et al., 1986; Rhee et al., 1986).

The schematic circuit for the generation of square pulse is given in Fig. 10. The transmission line theory explains the formation of a square pulse as follows. A transmission line of length ℓ and of characteristic impedance $Z_0 = (L/C)^{1/2}$ is initially shorted at both ends and charged with a constant current I_0. The charging current can be considered as the superposition of two traveling waves of constant voltage amplitude $V^+ = -V^- = Z_0 I_0/2$ and accompanying currents $I^+ = I^- = I_0/2$, proceeding in opposite directions, each being constantly reflected from the shorted ends satisfying the boundary conditions, i.e., reflection coefficients $\rho = -1$. The resultant voltage along the line is zero while the current is equal to the charging current I_0. When one end is suddenly opened by the opening switch, which is connected in parallel with a resistive load of maching impedance, the positively traveling wave no longer reflects and proceeds towards the load forming a rectangular pulse. The resultant output has a voltage $V_{out} = Z_0 I_0/2$, a current $I_{out} = I_0/2$, and a pulse duration $\tau_{out} = 2\ \ell/c$. A 6 meter long RG-58 coaxial cable providing a 60 ns pulse has been used as CCTL in most of these experiments. The amount of charging current in the CCTL is limited by the switch resistance in the conductive state (R_{on}) and the bias voltage as: $I_0 = V/R_{on}$.

The square pulses obtained with several switches are shown in Fig. 11. The slightly noisy appearance of the leading edge of the pulses was attributed to a large mode fluctuation of the argon laser observed at a frequency of 100 MHz

corresponding to its cavity length. The faster rise times were obtained with the GaAs:Cr switch and one of the InGaAs switches (1.5 ns). When these switches are used, the limiting factor for the opening time was found to be the rise time (1 ns) of the Pockels cell. Similar to the lumped circuit inductive storage experiment, only for the GaAs switch #1, the opening time was limited by the material carrier recombination time. The interdigitated InGaAs:Fe switch was found to be not suitable for 10 Hz operation: the heat accumulation causes the density of carriers to continuously increase over several minutes while the carrier recombination time was degraded down to 10 ns (Fig. 12). For this reason, a single pulse operation was employed to obtain the result shown in Fig. 11 for this switch. The best ratio of the signal amplitude to the bias voltage was obtained with the interdigitated InGaAs:Fe switch (0.12). To improve this ratio, one has first to further lower the on-state switch resistance. When assessing the efficiency of the system, a factor to be taken into consideration is the energy transfer from the CCTL to the load. It can be studied in terms of the ratio of the output energy to the stored energy in the CCTL. The output energy is:

$$E_{out} = V_{out} \cdot I_{out} \cdot \tau \tag{7}$$

and the energy stored in the CCTL is:

$$E_{stored} = 1/2 \; \ell L \; I_0^2 \tag{8}$$

where L is the inductance of the line per unit length. Using the relation $\ell L = \tau Z_0/2$, the efficiency of the energy transfer can be written as:

$$R = (2V_{out}/Z_0 I_0)^2 \tag{9}$$

and has been measured to be very close to 100 percent.

Conclusion.

In conclusion, we have demonstrated for the first time the operation of a 1 ns rise time semiconductor repetitive opening switch. A number of semiconductor materials and gap configurations have been examined, and the different aspects of the device's response have been studied. Although in this work only 10 Hz repetition rates have been achieved, these switches are potentially capable of operating at a very high repetition rate. The opening of the switch is jitter-free with respect to the laser pulse. Its closing period, which is controlled by the light illumination, can be as long as needed. This technique can be scaled up to a high voltage/high current system provided that the switch material, and the wavelength and power of the light source are matched. For those reasons, the development of this type of opening switch for high power applications is very promising and worthwhile.

The generation of very fast rise-time and fall-time square pulses using a current charged transmission line and this opening switch was demonstrated. The energy transfer efficiency from the transmission line to the load was nearly 100 percent, making this new circuit configuration possible for high power applications.

ACKNOWLEDGMENTS

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TABLE I. Summary of the five switches examined.

Switch #	Material	Gap Size	Gap Geometry
1	GaAs	200 μm	single gap
2	GaAs	21 μm	single gap
3	Cr:GaAs	30 μm	single gap
4	Fe:InGaAs	4 μm	single gap
5	Fe:InGaAs	6 μm	interdigitated

CAPTIONS

Fig. 1. Experimental set-up. P is a polarizer.

2. Optical waveform showing cut-off of the light by the Pockels cell.

3. Examples of output voltage waveforms obtained in the lumped inductive storage circuit configuration. The GaAs switch #1 was used with $V = 20$ V,
$R_{on} = 12.5$ kΩ, $R_{off} = 85$ kΩ. No external capacitor was used.
a) $R_L = 573$ Ω, $L = 1.8$ μH, oscillatory
b) $R_L = 50$ Ω, $L = 20$ μH, overdamped

4. Output voltage waveform obtained with the InGaAs:Fe switch #4 for $R_L = 50$ Ω and $L = 20$ μH showing a 1 ns rise time.

5. Switch resistance as a function of the cw argon laser power.
a) Switch #2 with bias voltage 2 V, b) Switch #3 with 2.6 V,
c) Switch #4 with 2 V, d) Switch #5 with 0.7 V.

6. I-V curve of switch #4.

7. Response of switches in closing switch configuration.
a), b), c) Switches #3, 4, and 5, respectively.

8. Switch response for different bias voltages obtained in closing switch configuration -- the cw mode locked dye laser was used.

9. Switch response for different light intensity obtained in closing switch configuration. Switch #4 was used with the cw mode locker dye laser. It shows the saturation of the switch.

Fig. 10. Current Charged Transmission Line (CCTL) and opening switch.

a) Schematic representation of CCTL and opening switch system to produce a square pulse.

b), c) Current distribution before and after the opening of the switch.

11. Output waveforms of square pulse.

a) Obtained with switch #2 and bias voltage 5 V, b) Switch #3 and bias voltage 15 V,

c) Switch #4 and bias voltage 4 V, and d) Switch #5 and bias voltage 2 V.

12. Effect of temperature on switch #4 used in the configuration of Fig. 10.

a) 10 Hz operation,

b) single shot operation.

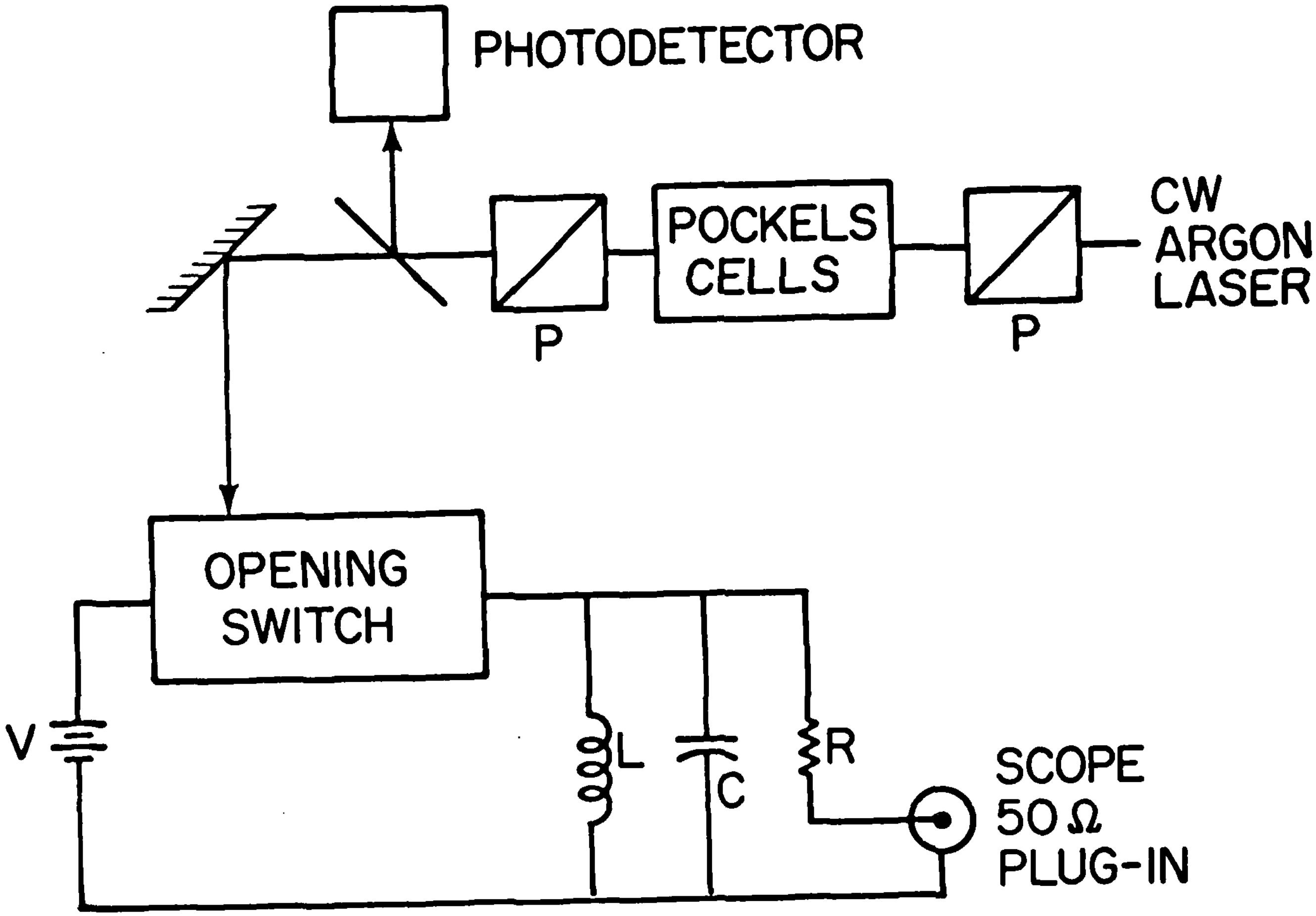

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Fig 1.

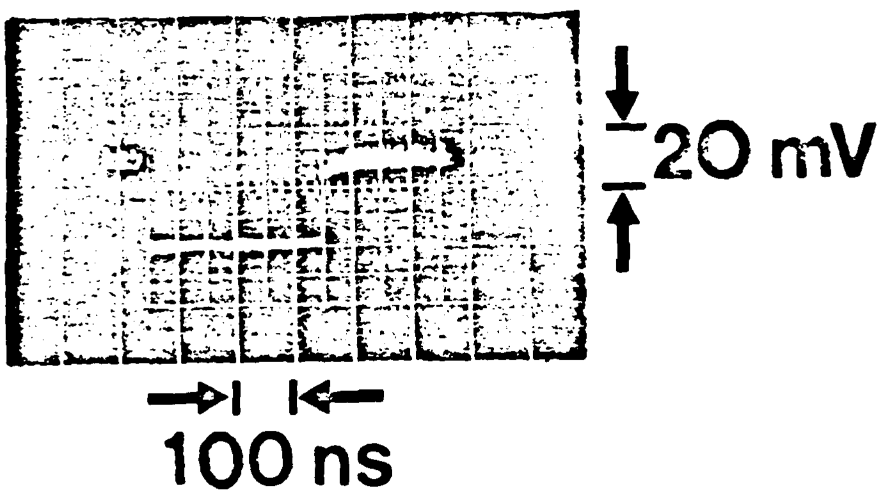


Fig. 2

Fig. 3

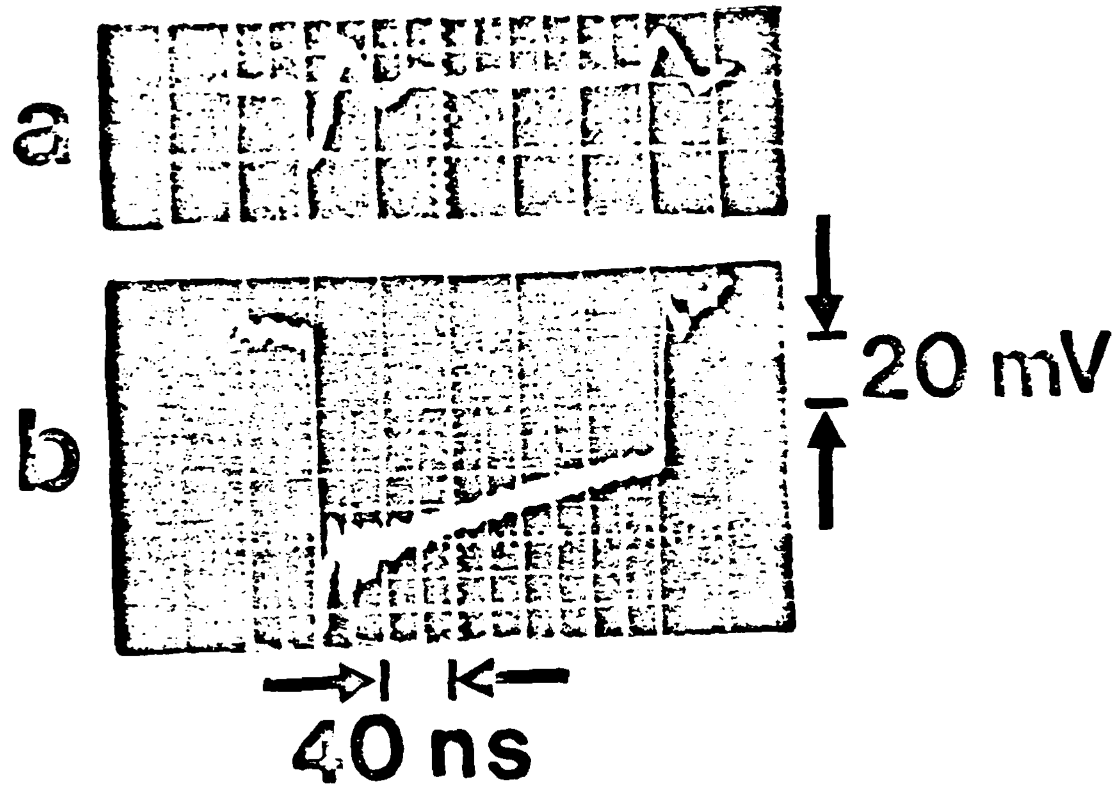
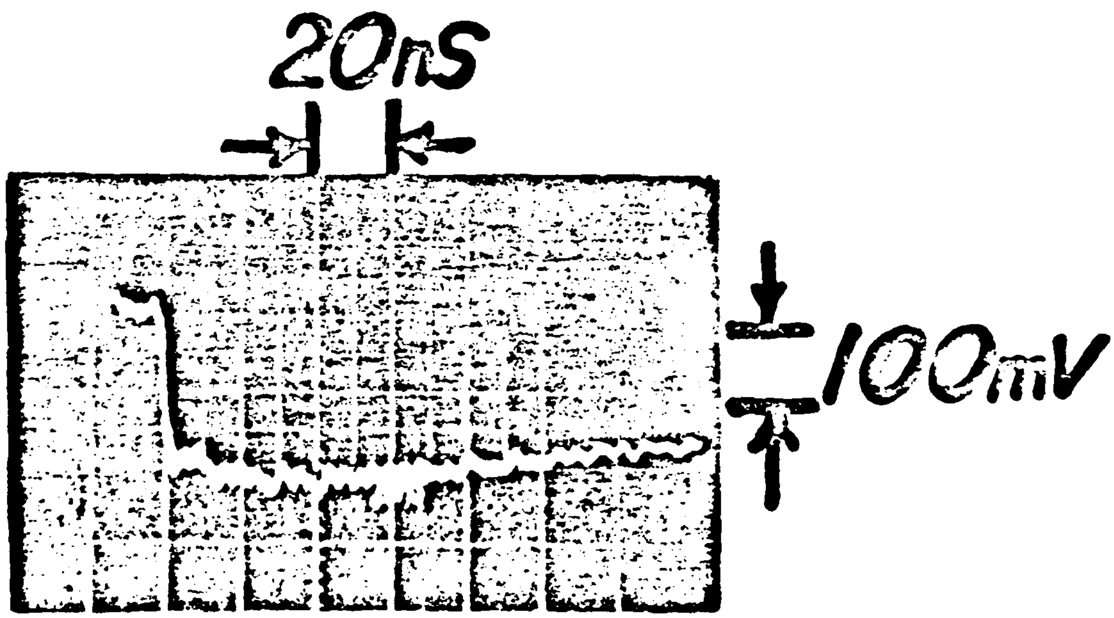
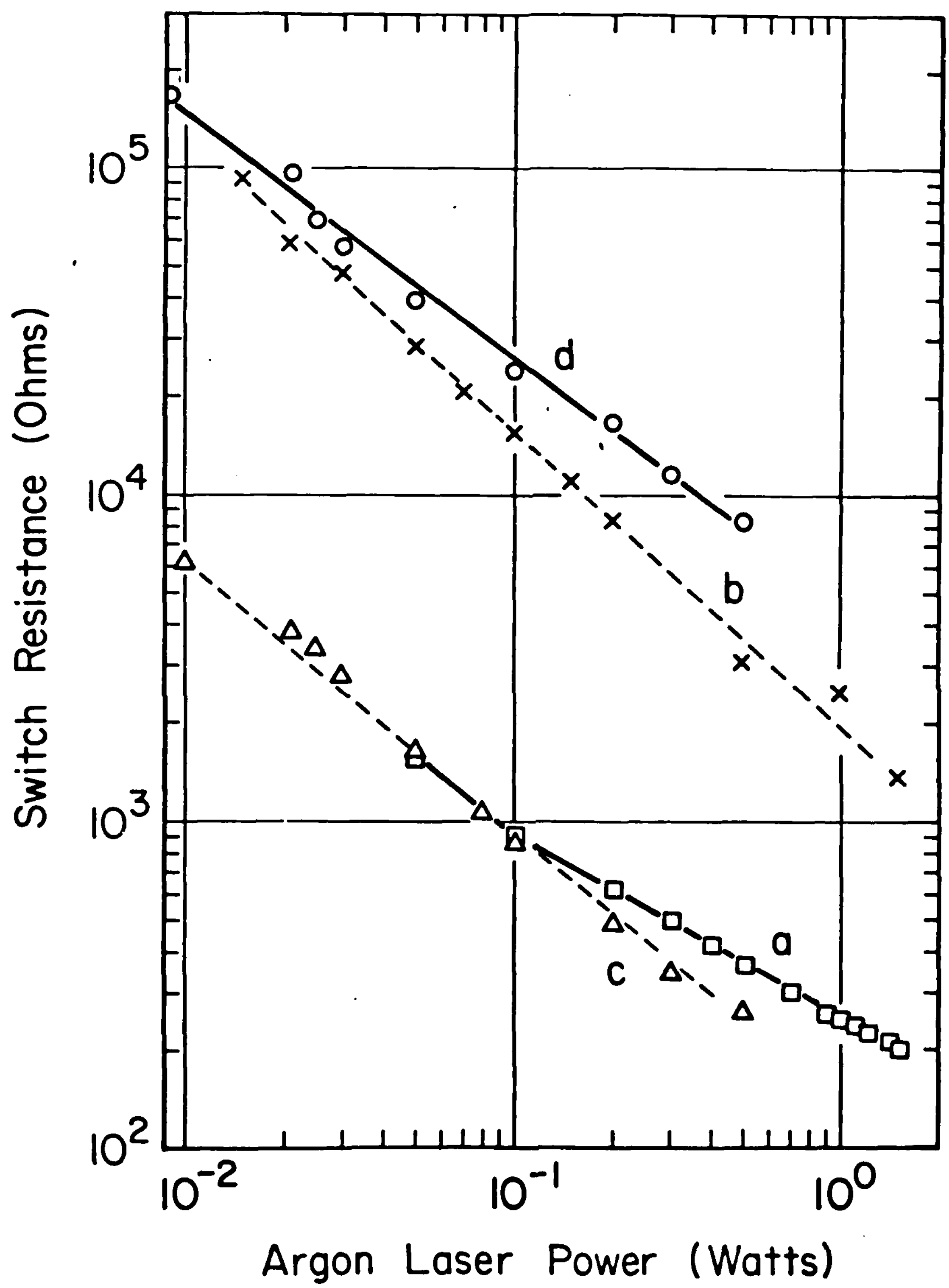


Fig. 4





Switch Resistance (Ohms)
10^5
10^4
10^3
10^2
d
b
a
c
10^{-2}
10^{-1}
10^0
Argon Laser Power (Watts)

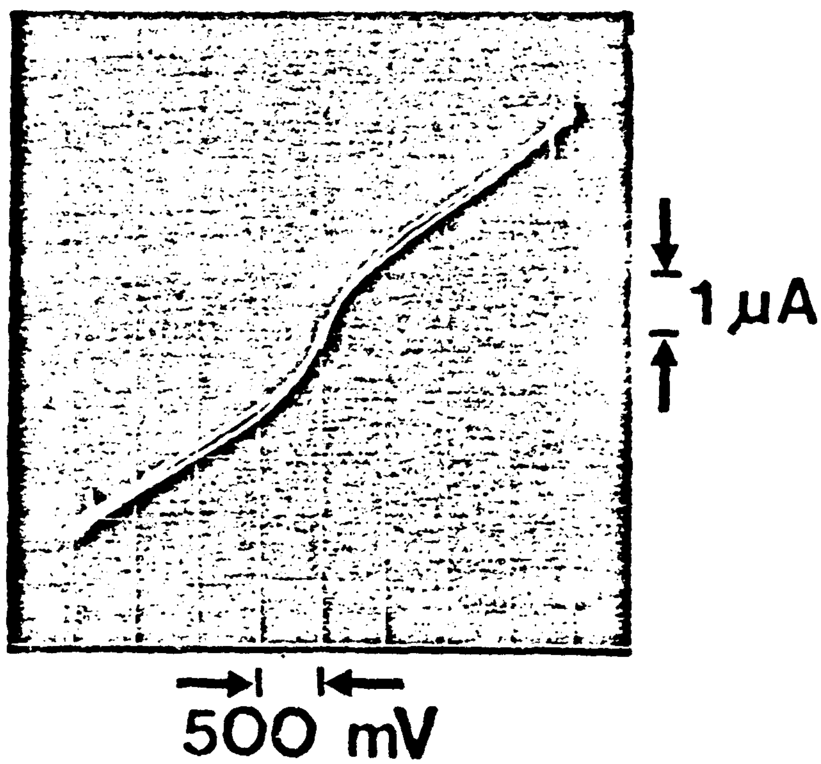


Fig. 6

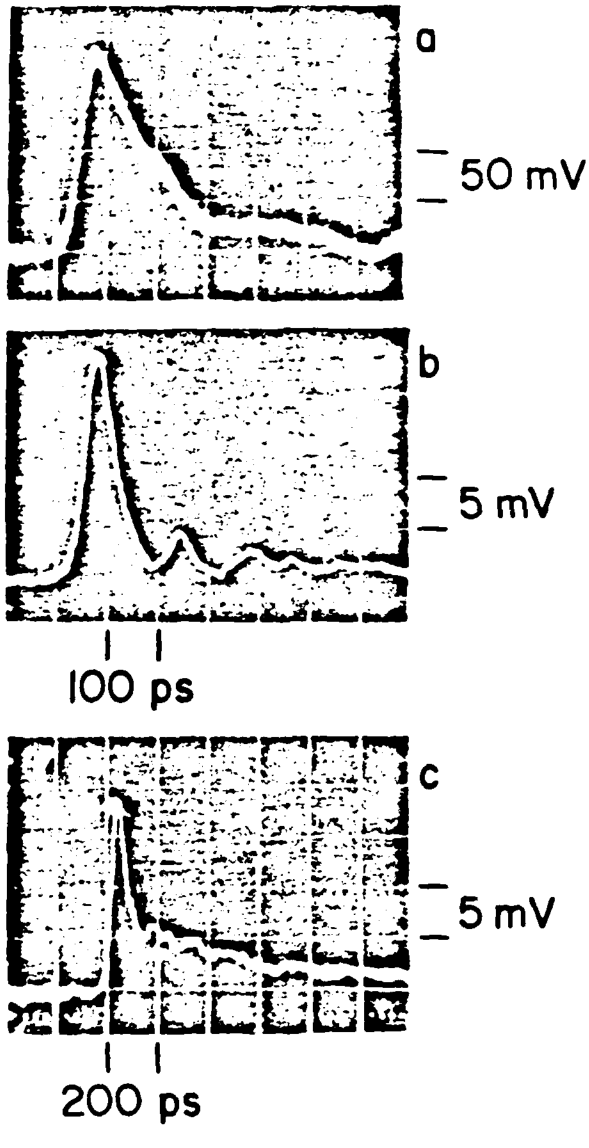


Fig. 7

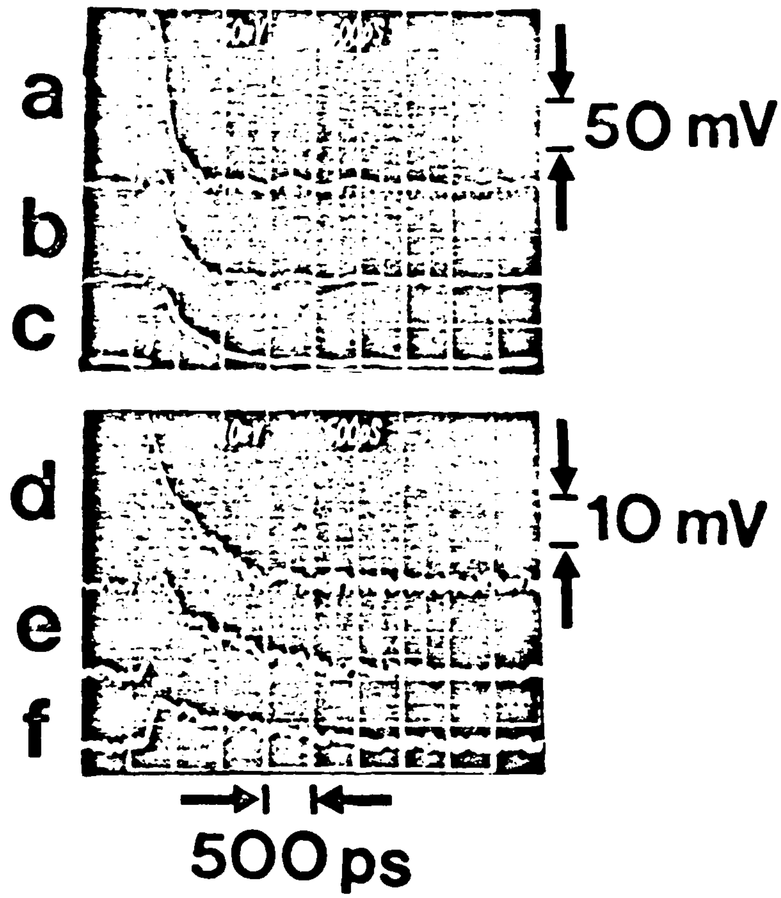


Fig. 8

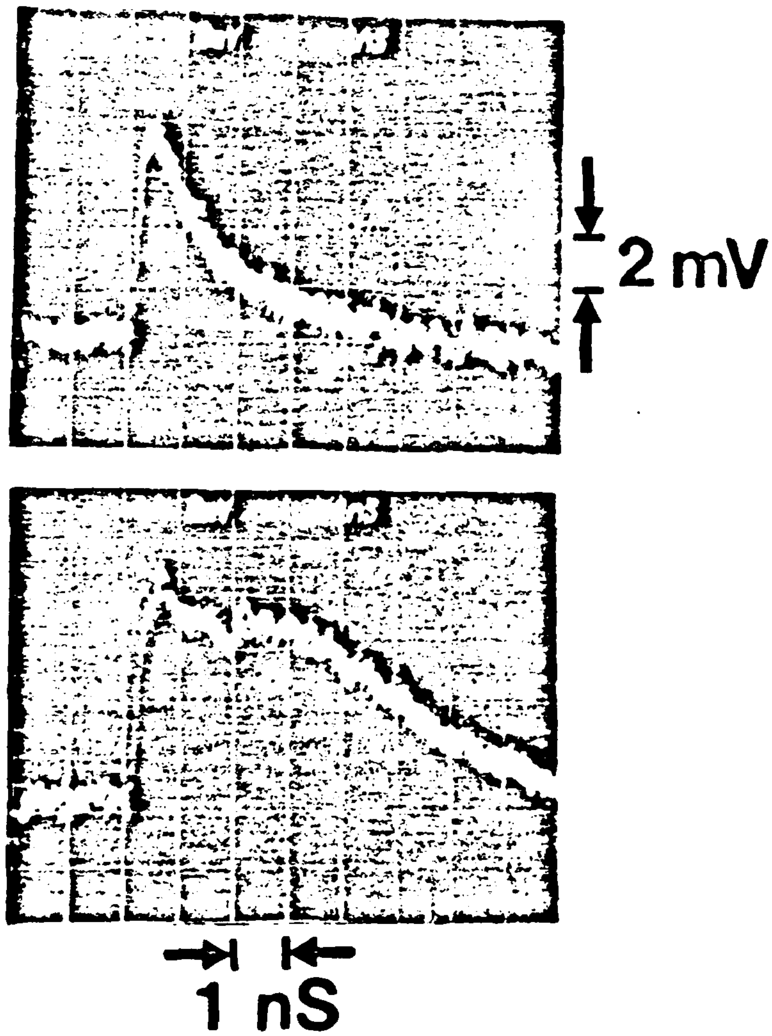


Fig. 9

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Fig 10
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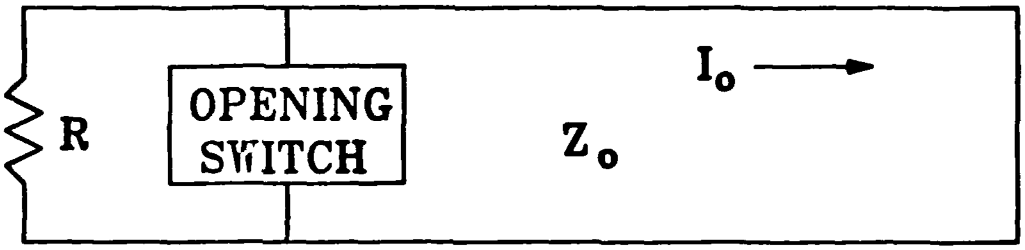
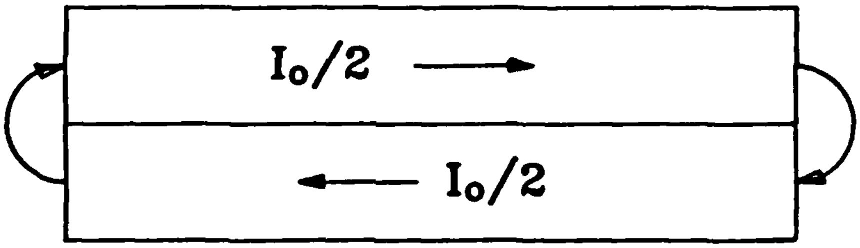


(a)



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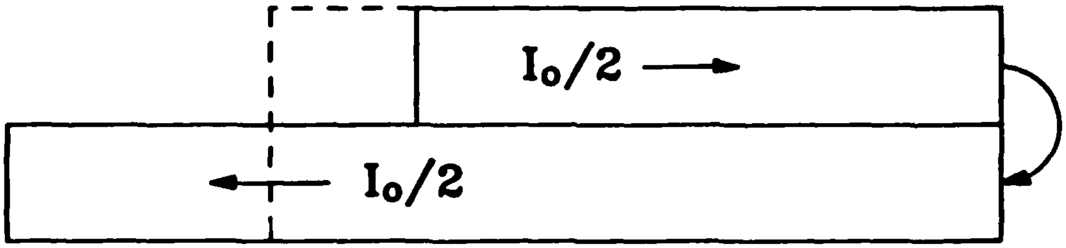

(c)

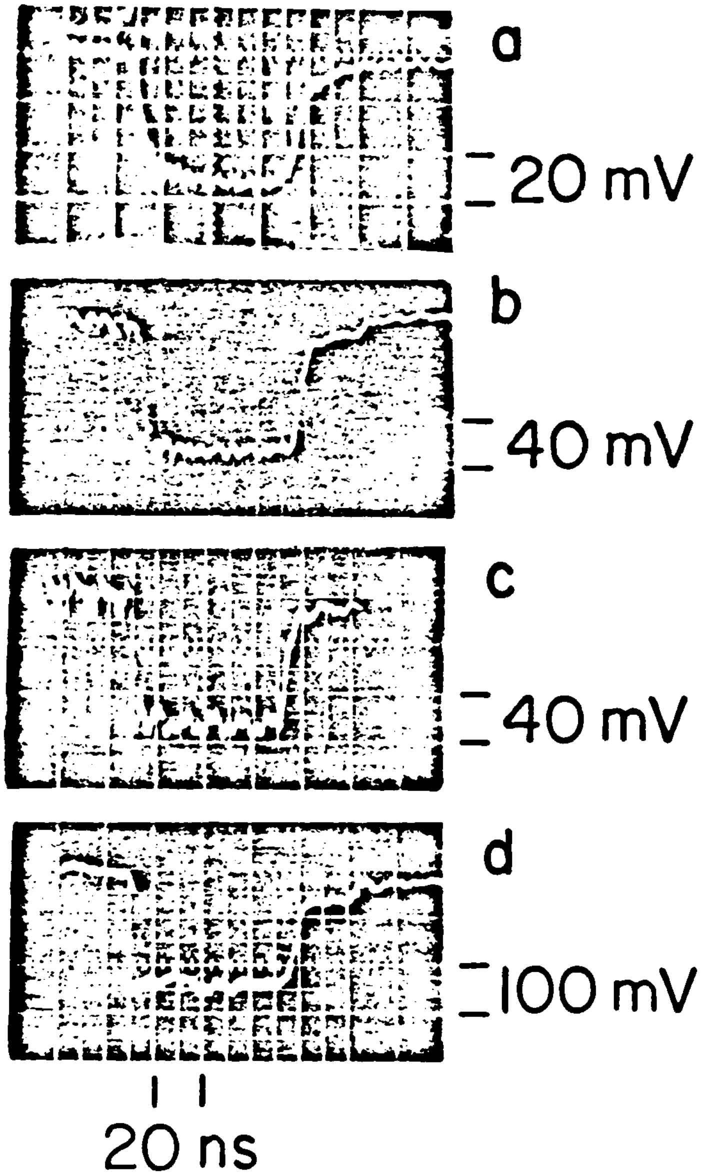

Fig. 11

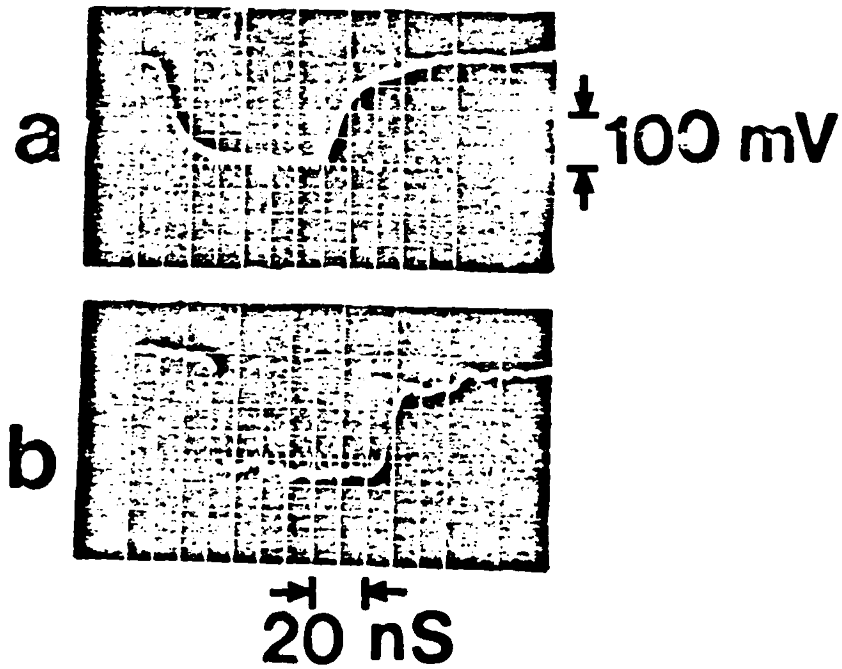

Fig 12

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